CHANGING WHAT'S POSSIBLE

Static Analysis of the WECC System with Continuous Variable Series Reactor (CVSR)

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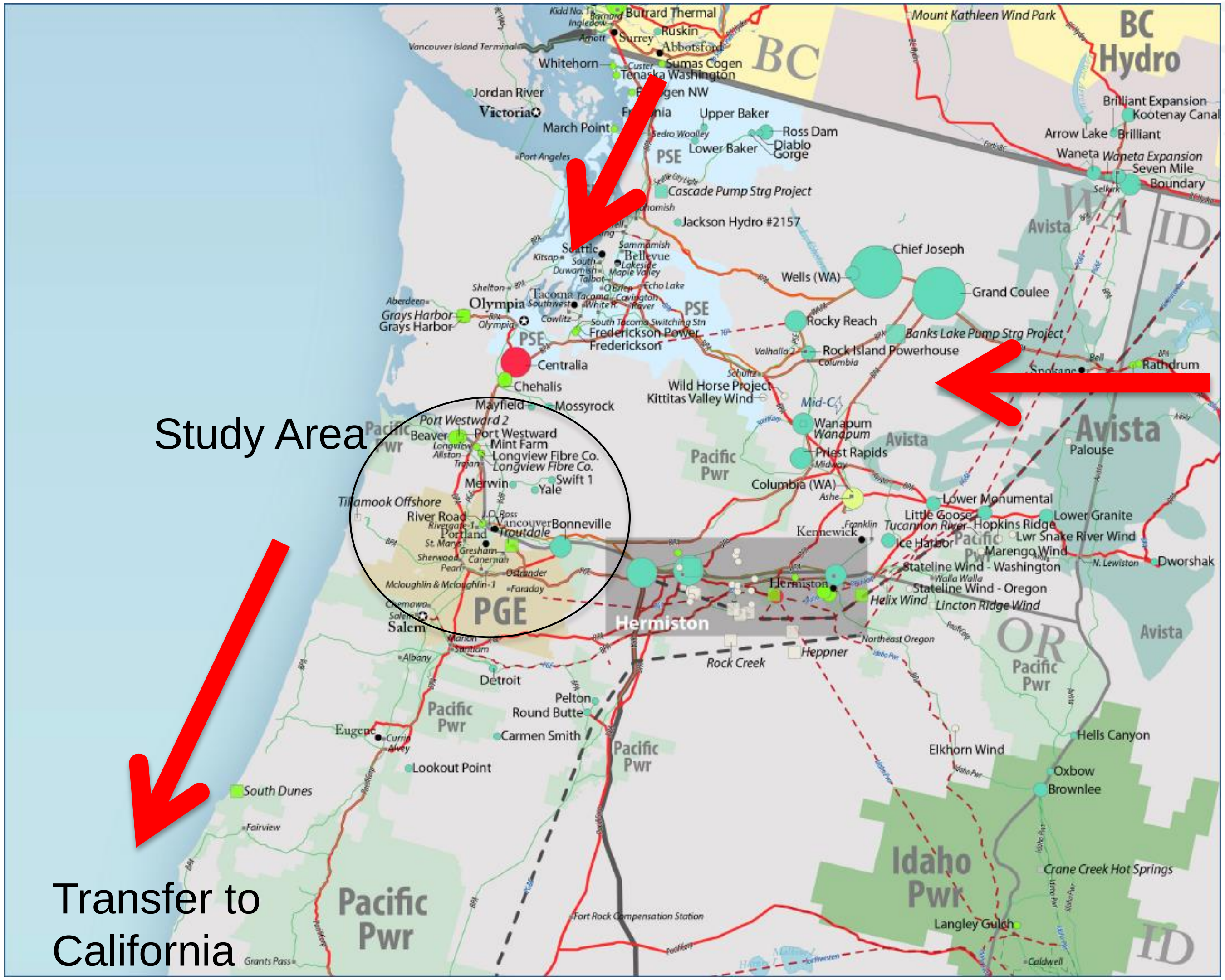
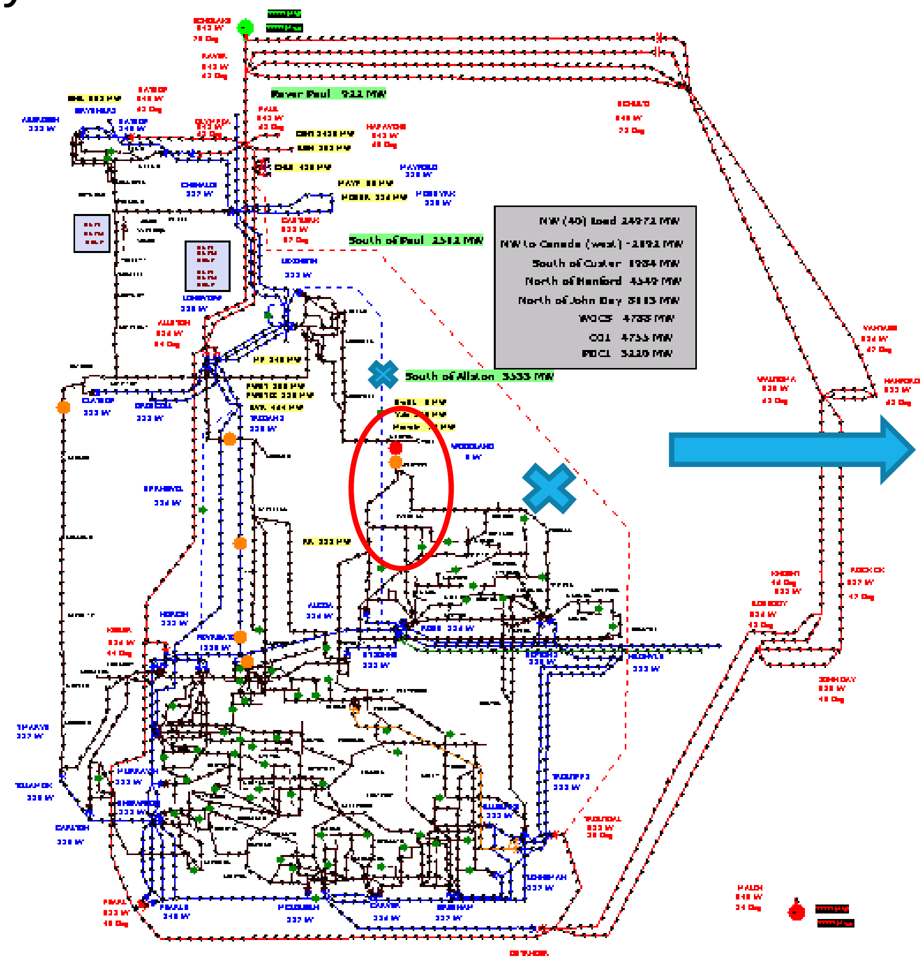
WECC – Northwest System Power Transfers



Example - Congestion Relief

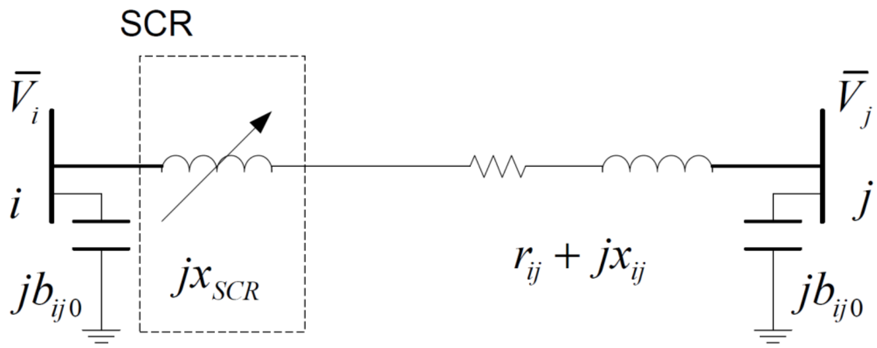
- The figure below shows one contingency case in the Northwest System.



- Loss of two transmission lines from North to South.
- The transmission line in the red circle becomes overloaded.

Optimization Model

- Static model of CVSR or saturable-core reactor (SCR)



- The overall impedance of the transmission line with CVSR is

$$z_{ij} = r_{ij} + j\left(x_{ij} + x_{SCR,ij}\right)$$

- The resulting conductance and susceptance are

$$g_{ij} = \frac{r_{ij}}{r_{ij}^2 + (x_{ij} + x_{SCR,ij})^2}$$

$$b_{ij} = - \frac{x_{ij} + x_{SCR,ij}}{r_{ij}^2 + (x_{ij} + x_{SCR,ij})^2}$$

Optimization Model

- Objective function: The loadability or load margin can be considered to be associated with the following three issues:
  - Voltage stability limit corresponding to a system singularity.
  - Generator reactive power limits.
  - Thermal or bus voltage limit.

$$\max \quad \xi$$

- Equality constraints: The active and reactive power balance equations:

$$P_{gi} - \xi \cdot P_{di} - g_i V_i^2 = \sum_{j \in B_i} P_{ij}, \quad i \in B_{LC}$$

$$Q_{gi} - \xi \cdot Q_{di} - b_i V_i^2 = \sum_{j \in B_i} Q_{ij}, \quad i \in B_{LC}$$

$$P_{gi} - P_{di} - g_i V_i^2 = \sum_{j \in B_i} P_{ij}, \quad i \in B_{NLC}$$

$$Q_{gi} - Q_{di} - b_i V_i^2 = \sum_{j \in B_i} Q_{ij}, \quad i \in B_{NLC}$$

- B_{LC}: Load center buses
- B_{NLC}: None load center buses
- B_i: Buses connected to bus *i*

Optimization Model

- Inequality constraints:
  - Physical limits
    - Bus voltage magnitudes:

      $$V_i^{\min} \le V_i \le V_i^{\max}$$

    - Power generation is limited by the capacity of the generators:

      $$P_{gi}^{\min} \le P_{gi} \le P_{gi}^{\max}$$

      $$Q_{gi}^{\min} \le Q_{gi} \le Q_{gi}^{\max}$$

    - Thermal limits for each transmission line:

      $$\sqrt{P_{ij}^{2} + Q_{ij}^{2}} \le S_{ij}^{\max}$$

  - Total reactance limits: To limit the number of CVSRs that can be installed in the system, the following constraint is introduced:

    $$\sum x_{SCR,ij} \le k_f \sum x_{SCR,ij}^{\max}$$

The WECC System

- The WECC system data from BPA, it is the 2018 summer peak case.
- The WECC system includes about 20,000 buses.
- We use the built in function “Equivalancing” in PowerWorld for model reduction:
  - The Northwest is the study system (WA, OR and ID).
  - The rest of the WECC is set to be the external system.
- The WECC is reduced to a system with 4016 nodes and about 4700 branches.
- The optimization task is to maximize the power transferred on the COI by installing several CVSRs in the Northwest power network.
- “Malin” and “Captain Jack” are the load center buses since they are the starting buses of the COI.

The WECC System

- During optimization, these parameters are fixed to their original settings:
  - Mvar switched shunts
  - Transformer tap ratios
  - Phase-shifting transformer angles
- The power injection from Canada can vary from 0 to 3000 MW, the power injection from West Montana is modeled as a negative load at boundary bus.
- Instead of fixing all generator bus voltage magnitudes to the originally regulated values, we relax the settings:

$$0.97V_g^{reg} <= V_g <= 1.03V_g^{reg}$$

- Not all generators can be rescheduled, 123 out of 416 generators are allowed to be rescheduled.
- The 115 kV lines owned by 5 utilities are considered as the candidate locations to install SCRs.

$$X_{SCR}^{\max} = 5.2 \times \frac{100}{115^2} = 0.0393\ p.u.$$

Simulation Results

- We analyzed 94 possible contingencies in the Northwest network and the worst 3 contingencies are presented here:
  - Contingency 1: One 500 kV transmission line from north to south is in outage.
  - Contingency 2: Two 230 kV transmission lines from north to south are in outage.
  - Contingency 3: Two 500 kV transmission lines from north to south are in outage.

- We consider 3 types of starting points for the optimization model:
  - Hot start 1: Power flow solution for the basic case
  - Hot start 2: Power flow solution for the case after the contingency
  - Cold start: Flat start.

Simulation Results

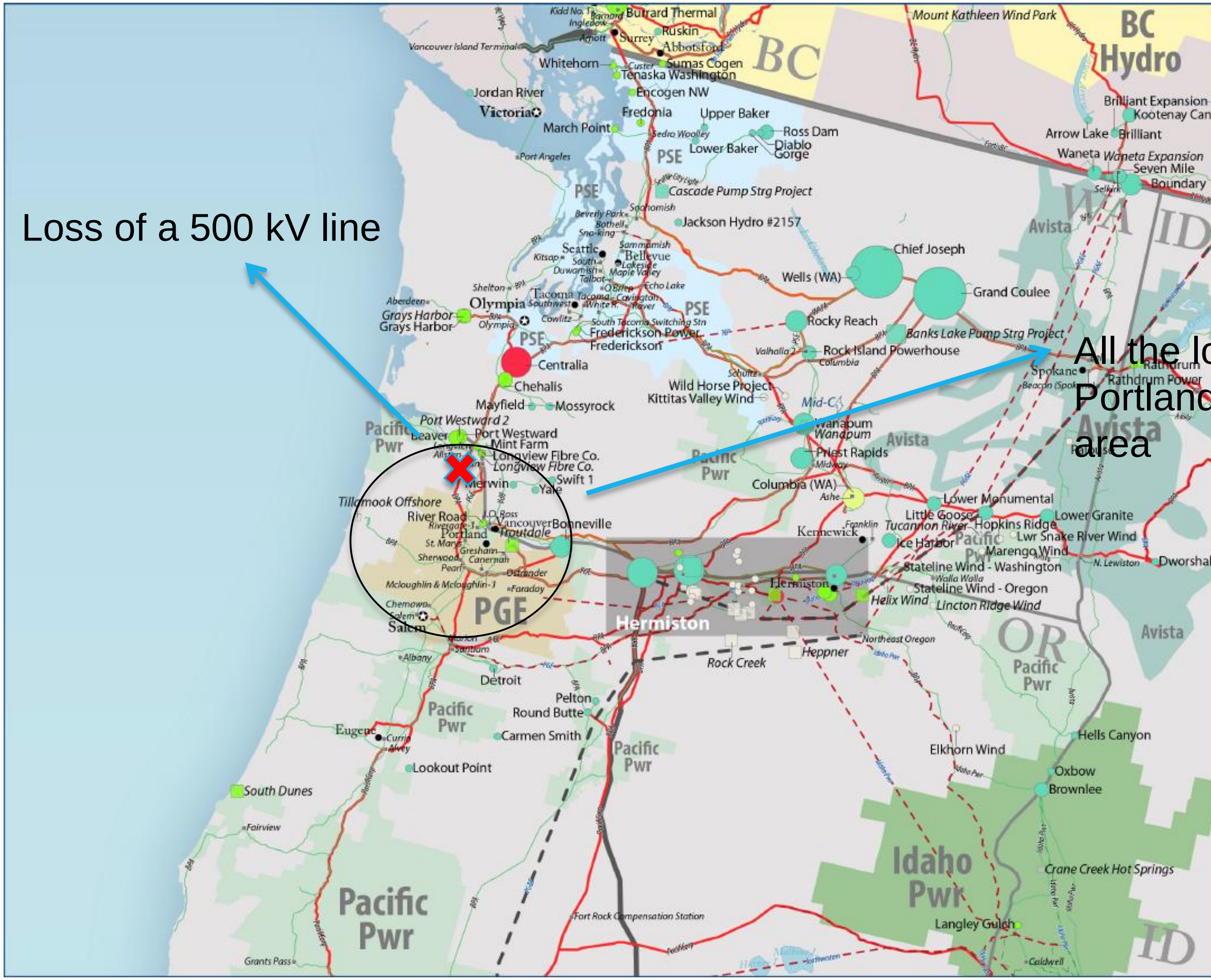
- The CVSR placement strategy of Northwest system:

Cont.	Start point	Branch #	Time (s)	ξ	ξ_0	ξ^*
	Hot start 1	576, 577, 779, 1177, 2721 2941, 3009, 3033, 3103, 4127	63,6	0.9553	0.8509	0.9740
1	Hot start 2	576, 577, 779, 1177, 2721 2941, 3009, 3033, 3103, 4127	57.0	0.9553	0.8509	0.9718
	Cold start	576, 577, 779, 1177, 2721, **2797** 2941, 3009, 3033, **3034**, 3103, 4127	116.4	0.9552	0.8509	0.9700
	Hot start 1	593, 599, 844, 2819 2858 2884, 3176, 3583	43.8	1.1012	0.9661	1.1060
2	Hot start 2	593, 599, 844, 2819 2858 2884, 3176, 3583	58.0	1.1012	0.9661	1.1055
	Cold start	**203**, 593, 599, 844 **926**, **2665**, 2858, 3176	290.2	1.1013	0.9661	1.1062
	Hot start 1	63, 389, 719, 844, 1298 2497, **2667**, 2858, 3009, 3176	44.9	1.0085	0.8491	1.0159
3	Hot start 2	389, 719, 844, 1298 2497, 2858, 3009, 3176	51.7	1.0085	0.8491	1.0156
	Cold start	63, 389, 719, 844, 1298 **2496**, 2497, 2858, 3009, 3176	473.9	1.0084	0.8491	1.0162

- ❑ ξ_0: Maximum loadability without CVSR.
- ❑ ξ^*: Maximum loadability when the total reactance limit constraint is removed.
- ❑ The red bold branch number is the slight difference of the SCR locations.

CVSR Locations (Contingency 1)

Loss of a 500 kV line



All the locations are in Portland, WA and OR area

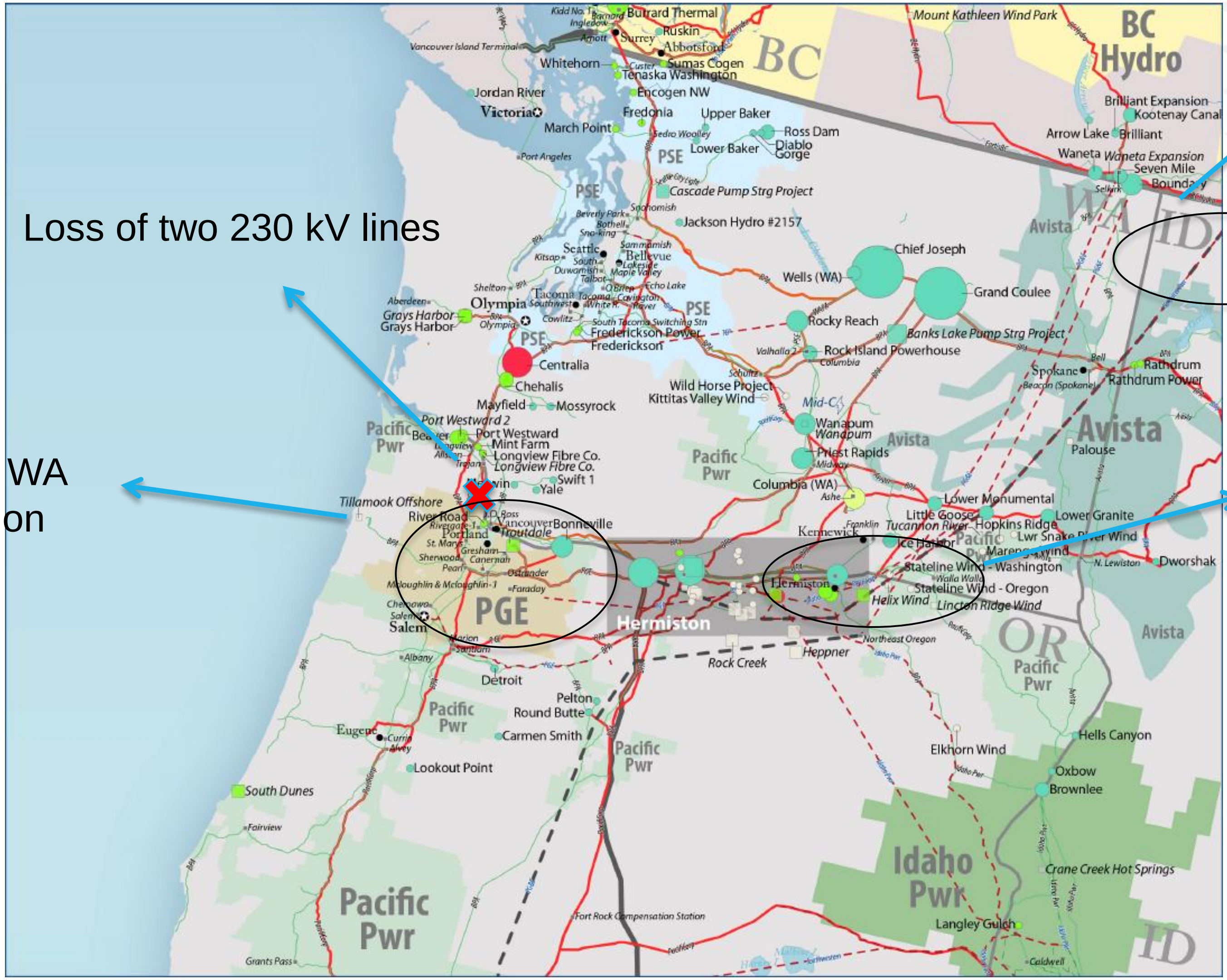
CVSR Locations (Contingency 2)

Loss of two 230 kV lines

Portland, WA and Oregon Area

West Montana

Lower Columbia Area



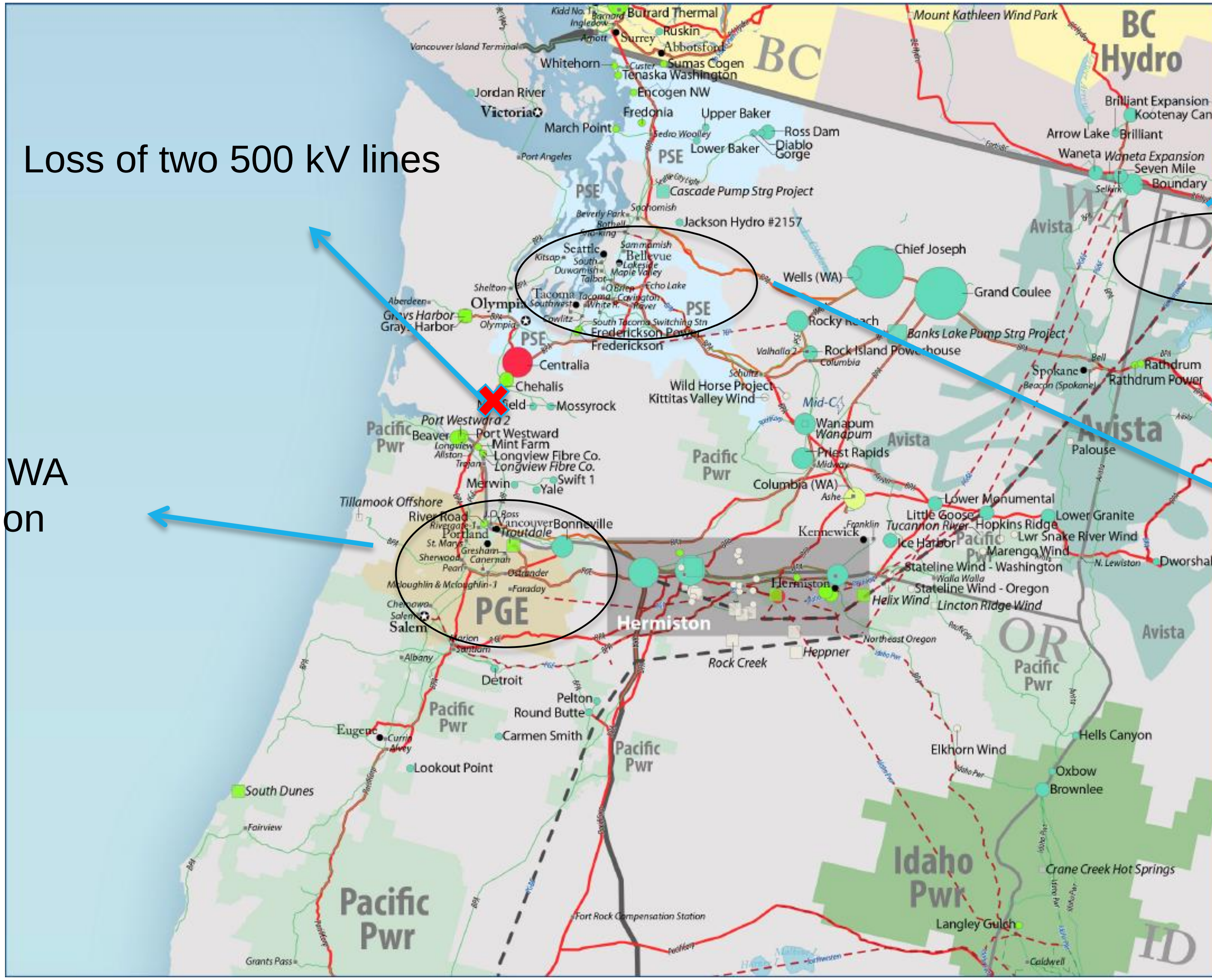
CVSR Locations (Contingency 3)

Loss of two 500 kV lines

West Montana

Portland, WA and Oregon Area

Seattle Area



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Simulation Results

- Most of the CVSR locations are the same when using different starting points.

- The model with cold start gives the longest computation time, which can be 10 times of the hot start model.

- The better utilization of the COI can be achieved by installing several CVSRs. For example, in contingency 1, the amount of power that can not be transferred to California is reduced from 15% to 4.5% with 10 CVSRs.

Simulation Results

- To implement on-line analysis of the optimization tool, we fix the CVSR locations to 4 branches: 2497, 2819, 2941, 3009 (All of them are in Portland, WA and OR area).
- SCR settings for different contingencies:

Cont.	x_{SCR} (p.u.)				Tims (s)	
	2497	2819	2941	3009		
1	0	0.0393	0.0393	0.0063	37.02	0.9477
2	0	0.0393	0	0.0277	25.12	1.0942
3	0.0393	0.0393	0	0.0393	30.61	0.8741

- Thermal loading of the main transmission paths from North to South for contingency 1.

Voltage level	115 kV		230 kV			500 kV
Branch #	2456	3009	842	2246	2415	78
Before cont.	62.6%	86.3%	30.2%	73.1%	65.9%	38.8%
After cont.	84.7%	107%	55.4%	104%	94.8%	60.3%
Without SCR	78.1%	100%	47.2%	95.9%	88.3%	54.0%
With SCR	80.9%	100%	50.5%	99.3%	91.7%	57.3%

Simulation Results

- For contingency 1 and 2, the loadability improves a lot with just 3 and 2 CVSRs respectively. For the contingency 3 with the least improvement, there is still about 2.5% of the power increase on the COI.

- The installation of the CVSR can redistribute the power flow and push more power from North to South through paths which still have transfer capability.

- For contingency 1, except for the fully loaded branch 3009, all the other paths from North to South will have loading increase. More power can be delivered to the South and transferred on the COI.

Conclusion and Future Work

- With several well located CVSRs in the power system, the system loadability and maximum power transfer capability can be greatly improved after the contingency.

- The optimization tool is suitable for both off-line planning and on-line analysis. The high computational efficiency and accuracy enable its direct application in the power system optimization analysis.

- Future work involves finding the critical locations of SCRs without running all the contingencies.

Acknowledgements

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